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## **Crystal Extraction of Beam from High Energy Hadron Accelerators**

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# Crystal Extraction of Beam from High Energy Hadron Accelerators

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## I. Introduction

It is an honor to have been asked to give the invited paper on this topic here at Dubna, for it was at Dubna where bending beams with channeling in a bent crystal was first observed under the leadership of former JINR member Edic Tsyganov. It was also at Dubna where a beam was first extracted from the circulating beam.

This paper will report only the results of the crystal extraction experiments at Fermilab and CERN. The very recent high-efficiency result obtained at IHEP, Protvino, will be presented in the next paper by Kotov.

## II. Fermilab Experiment 853.

This paper will summarize the experimental techniques and results of E-853, but will refer to formal publications for figures and details. What this paper adds to the published results is some interesting details about the planning and execution of the experiment not normally contained in formal publications.

### A. History

The motivation for E-853, which was proposed in 1991, was the desire to extract beam from the halo of the SSC for a fixed target B experiment. The idea of extracting the SSC halo, rather than scraping it on absorbing collimators, was first mentioned by C. R. Sun in 1984 [1]. The purpose of E-853 was to answer a number of questions relevant to the SSC proposal in a similar accelerator, the 900 GeV Tevatron, a superconducting accelerator like the SSC was to have been. The goals of the experiment were:

1. to extract  $10^6$  protons/sec with  $10^{12}$  protons circulating, or  $10^7$  protons/sec with  $10^{13}$  protons circulating;
2. to show that the luminosity lifetime is not seriously shortened;
3. to show that no intolerable backgrounds were created at the collider experiments;
4. to explore methods of creating additional halo using RF noise or damper noise.

There was also a slight concern that the particles scattered from the crystal might create sufficient energy deposition in the cryogenics of the Tevatron that the experiment would induce quenches of the magnets. This never happened during the course of the experiment.

The experiment was proposed in June, 1991. In April, 1992, it was approved for 72 hours of running in proton-only stores in the Tevatron, provided that the SSC would pay for the equipment. In December, 1992, the SSC granted \$100,000 for equipment, of which only \$70,000 was spent.

After a building and installation phase, and waiting for the Tevatron to switch from fixed target to collider mode, the experiment received 19 brief (~ 2 hours) study sessions with proton-only stores during 1995 and 1996.

The stores, in which E853 was the only user of the beam, were usually scheduled on very short notice, as it was advantageous to schedule the experiment during unexpected periods when there were not enough antiprotons for a collider experiments fill - for instance, after an unexpected power outage. The total study time in this mode was 57 hours.

Late in 1996, the experiment was allowed to run during the last few hours of a colliding beams store, provided that it was "unnoticed" by the collider experiments, meaning that the presence of the crystal close to the beam did not create objectionable backgrounds for the experiments. An additional 23 hours of study were received in this mode and allowed the accomplishment of goals 2 and 3 mentioned above.

### B. Apparatus

Details of the apparatus have been published [2,3] and will only be summarized here. The C0 straight section of the Tevatron was selected for the experiment, as there already existed there an extraction channel for the proton abort line which was not used at 900 GeV during the collider mode. A bent crystal replaced the first kicker magnet of the abort system and bent protons from the halo of the beam up into the abort channel. (see Fig. 1, ref [3]).

Silicon crystals of dimensions 3 x 9 x 39 mm with the (111) atomic plane parallel to the top face were fabricated and characterized by the Petersburg Nuclear Physics Institute, Gatchina. The crystal was bent through 0.64 mrad in a four-point spring-loaded bender. The bender with the crystal was mounted inside a one-meter vacuum tube which had vertical and horizontal stepping motors at each end and served as the goniometer for aligning the crystal angle to the beam angle. The smallest goniometer step size was 2.5  $\mu$ rad, in order to be smaller than the crystal critical angle of 5.2  $\mu$ rad and the beam angular divergence of 11  $\mu$ rad.

Extracted beam was detected with instruments in two air-gaps in the extraction channel situated 60 and 100 m downstream of the crystal. Both air gaps had a pair of scintillators in coincidence to count the beam, and the first air gap also had a fluorescent screen viewed by a CCD camera.

An additional scintillator, called the interaction monitor, was placed directly underneath the goniometer in order to measure the interaction rate of the protons with the crystal.

### C. Operations

At the beginning of a study session, the crystal was gradually moved horizontally into the halo from the outside of the ring. Note that in contrast with the CERN experiment, the crystal moved into the beam in the horizontal plane but bent the beam up, so that any lack of parallelism between the atomic planes and the

top optical surface would not reduce the extraction efficiency. The final distance of the crystal from the beam center was between 4 and 7 mm, depending on the beam intensity or luminosity. This distance was chosen to maximize the extraction rate consistent with other constraints (see below).

In the proton only stores, the experiment operated in two modes. In the first, called kick mode, a single beam bunch was given a fast angular kick so as to be 0.5 mm closer to the crystal two turns later. The purpose of this mode was to get beam deep into the crystal past the imperfectly aligned crystal surface facing the beam. This mode was very useful for achieving the initial alignment of the vertical and horizontal faces of the crystal to the beam angles.

This mode also proved definitively the importance of multi-turn extraction: protons which were not within the critical angle of the crystal during their first encounter are multiple scattered and could return on a later turn with an angle less than the critical angle and were then extracted. These results are discussed in detail in Ref. [2].

The second mode used, called diffusion mode, depended on noise sources such as beam-gas scattering, power supply modulation, and magnetic field non-linearities to produce beam growth so that beam gradually and steadily diffused onto the crystal. The mode was used exclusively during colliding beam stores, where the beam-beam interaction at the two collision points creates a large halo, and was called “luminosity-driven” diffusion.

## D. Extraction Rates

The extraction rates were measured under three conditions: extraction driven by natural diffusion during proton-only stores, RF noise-driven diffusion during a proton-only store, and luminosity-driven extraction during proton-antiproton stores.

In a typical proton-only store,  $10^{11}$  protons were circulating in six bunches. In this mode, the maximum extraction rate achieved was 200 kHz. Higher rates could have been achieved by moving the crystal even closer to the beam, but with only six bunches, a rate of 287 kHz corresponded to extracting on average one proton per bunch, and the counters could not count more than one particle per bunch.

To mitigate this limitation, a special store was arranged with  $10^{11}$  protons circulating in 84 bunches. Additional diffusion was induced by transverse RF horizontal noise using the electrical damper located at F11, creating an rms diffusion rate at the crystal of  $0.023 \mu\text{m}$  per turn. The extraction rate was greater than 450 kHz.

In the luminosity-driven stores, typically  $10^{12}$  protons were circulating in six bunches. The maximum extraction rate achieved was 150 kHz. In this mode the limitation was the impact of particles scattered from the crystal in creating backgrounds for the operating collider experiments. Although the CDF experiment received no measurable background from the crystal, the D0 “lost proton” monitor was sensitive to scattering from

the crystal. D0 was usually already running at 80% of the conservative upper limit set by that experiment before the crystal was moved close to the beam and reached the limit when the extraction rate was between 50 and 150 kHz.

This limitation was removed during a special store with 36 proton bunches and 3 antiproton bunches during which D0 was not taking data. There were  $3 \times 10^{12}$  protons circulating, and an extraction rate of 900 kHz was achieved. The D0 lost proton monitor exceeded its upper limit by a factor of 1.5 before the crystal was inserted, and exceeded the limit by a factor of two after the crystal was inserted.

## E. Extraction Efficiency

Another purpose of this experiment was to measure the extraction efficiency. “Efficiency” in this context is defined in two ways. One practical definition, which we call the “extraction efficiency”, is the extraction rate divided by the increase in the total circulating beam loss rate after the crystal was inserted. This definition was used by CERN.

While the numerator was straight-forward to measure, determining the change in the total loss rate from the accelerator was difficult. The variation with time of the loss rates before the crystal was inserted, resulting from various instabilities in the accelerator, usually exceeded the difference between the crystal out and in loss rates.

No measurements of this efficiency were possible. However, it was possible to determine a 90% confidence lower limit to the extraction efficiency during two proton-only fills, which was 30%.

A second way to measure the efficiency is to compare the number of protons that interact with the crystal when its vertical angle is not aligned to the beam with the number that interact when it is aligned for maximum channeling. Fewer interactions are observed when the crystal is well aligned with the beam because the channeled protons do not come close to nuclei. We call this the “channeling efficiency” and define it as the difference between the aligned and unaligned interaction monitor rate, divided by the unaligned rate.

However, this efficiency is expected to be slightly higher than the extraction efficiency (by a factor of about 1.35 in a simple model), because protons which are dechanneled after being only partially bent contribute to this reduction in interaction rate, but are not extracted, instead being lost on apertures of the accelerator.

In operation, the interaction monitor rates were sensitive to fluctuations arising from such effects as small horizontal fluctuations of the circulating beam. Some of these effects could change in an unpredictable way in the time it took to do a typical  $\Theta_V$  scan. To mitigate this time dependence, the best measurements were obtained by moving the crystal quickly back and forth from an aligned to a very unaligned vertical angle.

In two stores in which the extraction was luminosity driven, the channeling efficiencies were  $24 \pm 8\%$  and  $35 \pm 11\%$ . During the 84-bunch proton-only fill, the efficiency was  $32 \pm 9\%$ . The errors in these efficiencies are derived from the rms scatter of the many data points about their average value. A simulation of the experiment [4] predicted an extraction efficiency of 35% for a realistic crystal.

The average channeling efficiency is thus  $30 \pm 6\%$ , leading to an estimated extraction efficiency of  $\sim 23\%$ .

### III. CERN Results

For many years, the experiment known as RD22 has been studying bent crystal extraction in the SPS, usually at an energy of 120 GeV. The results have been extensively published [5,6,7] but will be summarized here and compared with other results.

The geometry of the CERN experiment differed from the Tevatron geometry in that the beam was brought onto the crystal in the horizontal plane, and the crystal also bent horizontally. Therefore, the crystal bender was more complicated to avoid obscuring more than a little bit of the area of this surface. Ultimately, the experiment made a monolithic “U” shaped crystal [5] for which the bending was effected by squeezing the two open legs of the “U”, leaving the bending surface completely unobscured.

The CERN experiment differed from the Fermilab experiment also in that the diffusion was nearly always driven with noise on a damper, leading to rather short lifetimes for the beam. No attempt was made to operate parasitically with other experiments.

The published results for extraction rate and efficiency are summarized in Table I.

TABLE I. CERN bent crystal extraction results at 120 GeV [5,6].  $I_c$  is the circulating intensity (sometimes not published).  $D$  is the distance of the crystal from the beam center,  $T$  is the beam lifetime, Rate is the extraction rate, and Eff is the efficiency. The amount of noise applied can be inferred from the lifetime: shorter lifetimes correspond to more noise.

$I_c$ ( $10^{11}$ p)	$D$ (mm)	$T$ (hrs)	Rate (kHz)	Eff (%)
	10	3.5	310	$4.1 \pm 0.8$
	10	0.6	250	$6.5 \pm 0.7$
	15	4.4	320	$8.3 \pm 1.0$
	20	3.0	510	$8.9 \pm 1.0$
	25	2.4	570	$10.0 \pm 1.5$
4.90		44.0	345	$10.6 \pm 2.6$
0.13		0.7	788	$15.4 \pm 2.2$
0.07		0.9	267	$12.4 \pm 1.4$
0.16		0.6	948	$13.0 \pm 2.2$

It can be seen that the highest efficiencies were achieved with the short lifetime stores, corresponding to

a large amount of noise. Nonetheless, an efficiency of 10.6% was achieved with a very long lifetime of 44 hours, perhaps corresponding to no noise applied to drive the diffusion.

CERN has also recently measured the extraction efficiency as a function of the energy of the SPS [7]. The results are presented in Table II. The efficiencies shown in the table are the *highest* achieved at each energy. The improvement in efficiency between 14 and 120 GeV is dramatic.

TABLE II. Extraction efficiency as a function of energy of the CERN SPS. The efficiencies shown are the highest achieved at each energy. The simulated extraction efficiency has been normalized to the experimental result at 120 GeV.

SPS beam energy (GeV)	Extraction efficiency (%)	Simulated extr. efficiency (%)
14	$0.55 \pm 0.3$	0.48
120	$15.4 \pm 2.2$	15.4
270	$18.6 \pm 2.7$	18.0

CERN has also recently extracted fully ionized Pb atoms with the same bent crystal at energies of 22 and 33 TeV, corresponding to 270 and 400 GeV per charge [6]. Efficiencies were measured at 22 TeV and range from 4% to 11% - very similar to the results with 120 GeV protons.

### IV. Summary of Results

Beams have now been extracted from proton accelerators with energies ranging from 8.4 GeV to 900 GeV. It is interesting to present all of these results for extraction efficiencies as a summary, Table III.

TABLE III. Extraction efficiencies at various proton accelerators. For CERN and Fermilab, the efficiencies listed are the highest achieved.

Accelerator	energy (GeV)	efficiency (%)
JINR (Dubna)	8.4	$\sim 0.01$
IHEP (Protvino)	70	$\sim 0.10^{**}$
SPS (CERN)	14	0.55
	120	15.4
	270	18.0
Tevatron (Fermilab)	900	26
** not the most recent result (see text)		

It is, of course, not fair to compare these results and claim to have measured a grand energy dependence of extraction efficiency. This efficiency depends on too many factors which are different at each accelerator. Some of these factors are the length of the crystal, the

ratio of beam divergence to the critical angle, the distance of the crystal from the beam, and what mechanism drives the halo.

Nonetheless, the trend is interesting: the efficiency keeps rising with energy, nearly monotonically.

It has been known for some time from simulations that there is a crystal length which optimizes the extraction efficiency, and this length is energy dependent. When multi-pass extraction was properly simulated [4], this optimum length turned out to be much shorter than for one-pass extraction. For instance, at the Tevatron the optimum length is 15 mm (leading to a predicted efficiency of 70%), whereas the actual crystal length was 40 mm. This same disparity between optimum and actual lengths was generally true for all previous experiments

Very recently, a group at IHEP, Protvino, has constructed and bent an especially short crystal (5 mm) and extracted beam with it. They have achieved the world record efficiency of 45%. The details are the topic of the next paper.

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